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THESIS

ANTENNA AND STABILIZATION CONSOLE
FOR A VLF RELATIVE NAVIGATIONAL SYSTEM

by

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ABSTRACT

A VLF relative navigational system makes use of the fact that, at any given point on the earth, phase delay of a received VLF signal is highly stable and predictable. As the receiver is physically moved, phase delay changes linearly with distance from the transmitting station, so that by keeping track of the phase delay of the received signal from several VLF stations, an accurate plot of geographical position is maintained.

This paper outlines the development of a relatively simple antenna system, composed of two crossed loops and a whip sense antenna to produce a cardiod shaped radiation pattern, which effectively discriminates against the long-way-around-the-world contamination on the short path signal. A means is also devised for electronically rotating the fixed antenna by means of a goniometer which may be stabilized in azimuth by an input from a ship's gyrocompass.

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I. INTRODUCTION

The highly stable and predictable phase delays of received transmissions in the very low frequency (VLF) portion of the electromagnetic spectrum provide the basis upon which a long range VLF relative navigational system has been proposed. Such a system would be composed of a frequency stabilized transmitting station, a receiving antenna with an associated VLF phase tracking receiver, and an accurate local frequency standard. An initial comparison of the phase of the received transmission with that of the local frequency standard would be used to establish a reference phase difference. Any subsequent displacement of the receiver towards or away from the transmitting station would result in a relative change of the phase of the received signal, thus providing a measurement of the distance traveled.

If two or more transmitting stations are simultaneously tracked, they will provide a determination of position obtained by the intersection of several constant distance lines. Each such line is a circle of position about one transmitting station and with no reference to azimuth angle (circular grid system).[1] Herein lies the foundation of a navigational system whereby present location with respect to a reference

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[1]Stanbrough, J. H. Jr., and Keily, D. P., "Long Range Relative Navigation by Means of VLF Transmissions," in Deep Sea Research, vol. 11, 1964, pp. 251-252.

position may be continuously computed. Such a system would have world-wide coverage due to the long propagation paths of VLF transmissions.

In contrast to the LORAN, OMEGA and LORAC types of navigational systems, this system will not require any additional transmitting stations and can employ the existing VLF communication stations, a summary of which is provided in Section II. At the present time there are numerous VLF stations located so as to provide world-wide communications coverage for the U.S. Navy. Interruption of these signals (for CW broadcasting) will not affect the phase comparison process. Teletype keying of a known fixed frequency shift similarly does not affect phase measurement because the VLF phase tracking receiver is tuned to the frequency stabilized portion of the FSK signal. If the present VLF stations and their transmitting frequencies are maintained to a high enough frequency stability, no additional "navigational modulation" is needed; all that is needed is a receiving system. At the present time these stations are being controlled to within a part in 10^{11} of their assigned frequencies[2], and this stability is considered sufficiently accurate.

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[2] Stone, R. R. Jr., "Synchronization of Local Frequency Standards with VLF Transmissions," 18th Annual Frequency Control Symposium, in Frequency, 2, 4, July-August, 1964, p. 20.

The system as it has been proposed depends upon the frequency stability of both the transmitting station and the local standard, as well as a propagation path that is either highly stable or readily predictable. In recent years the development of extremely precise frequency standards enable the VLF stations to keep the frequencies of their transmissions to very close limits. In 1967 the Hewlett Packard laboratories were able to build a clock with a precision of 5 parts in 10^{14} using a Thalium beam. Highly accurate local atomic frequency standards provide phase reference with as little as 1-2 parts in 10^{11} drift per day. Further development work promises even greater accuracies. Propagation paths are highly stable when the path is either in total sunlight or total darkness, and they exhibit a diurnal shift with the value of the phase change caused by this daily shift being readily predictable.

Considerable effort has been expended proposing this world-wide navigational system,[3,4] as well as examining the factors which might degrade phase accuracy of such a system.[5]

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[3]Lake, LCDR. R. D., "An Investigation Into the Use of Very Low Frequency Transmissions for Ship Navigation," in Unpublished Master's Thesis, U.S. Naval Postgraduate School, Monterey, California, 1966, pp. 42-51.

[4]Stanbrough and Keily, op.cit., p. 249.

[5]McKay, LT. J. D. and Preston, LT. G. L., "An Investigation of Factors Which Degrade Phase Accuracy in a VLF Relative Navigational System," in Unpublished Master's Thesis, U.S. Naval Postgraduate School, Monterey, California, 1966, pp. 26-34.

Of particular interest is the recognition of the contamination on the short path signal by the long-way-around-the-world signal. Preston and McKay analytically and experimentally developed the concept of a cardiod shaped radiation pattern that eliminated long path contamination, while preserving a constant received signal phase over a large angular variation. This paper outlines the development of a relatively simple antenna system, composed of two crossed loops and a whip sense antenna to produce a cardiod shaped antenna radiation pattern, which effectively discriminates against this long-way-around-the-world contamination on the short path signal. Additionally, a means is developed for electronically rotating the fixed antenna by means of a goniometer which may be stabilized in azimuth by an input from a ship's gyrocompass. The combination of the crossed loop and whip antennas and the stabilized goniometer provide a shipboard means of continuous antenna positioning, thereby facilitating simultaneous tracking of two or more VLF transmitting stations.

II. VLF TRANSMITTING STATIONS

Before examining the factors which influence VLF propagation, a brief explanation of the existing stations, with particular emphasis on the phase-stabilized stations, shall be given.

Appendix A provides a listing of some 36 separate low frequency stations with their approximate frequencies. The particular range of frequencies extends from a low of 7.428 KHz for the Pontoise, France station, to a high of 233.0 KHz for Radio Luxembourg. Although some 36 stations are represented, there are 49 separate frequencies since several stations transmit simultaneously on more than one frequency. Within this listing are the 6 U.S. Navy stations, one National Bureau of Standards station, and one British Post Office station which provide scheduled broadcasts in the case of Navy stations, or time ticks in the case of the National Bureau of Standards and British Post Office stations.

Table I provides a summary of the above 8 phase-stabilized stations, in order of their increasing frequency, together with their locations, frequencies, sponsors, radiated power and type of transmissions. Table II indicates the off periods for the 6 U.S. Navy stations, as of 27 September 1968, and periods of reduced power operation. These off periods are varied occasionally hence reference should be made to the latest copy of Appendix B to establish optimal tracking intervals. In order to show more completely the aspect of world-wide coverage by the 8 phase-stabilized stations, Figure 1 indicates the locations of these stations on a chart of the world.

Subsequent to the proposal of this navigational system four additional VLF transmitting stations, comprising the OMEGA navigational system, have been built. The present four stations and four stations yet to be built will offer the opportunity of global navigation with relatively few transmitters. OMEGA signals are transmitted on a sequential, time-multiplexed basis. In order to be used in the proposed system these signals would have to be processed by a synchronized receiver commutation cycle to permit accurate phase measurement. The frequency stability of the OMEGA stations is superior to that of the 8 VLF stations, hence it would be more than sufficient for the proposed system.

In summary, these tables and chart indicate the available stations that might be used for the proposed navigational system, together with their respective powers and off periods. Selection of a particular station will depend upon the receiver location, with stations separated in bearing by nearly 90° providing the best crossing lines of position. Other factors, to be developed in the next chapter, will further influence the choice of a station due to propagation effects.

Figure 1. VLF stations.

STATION	Freq. (K Hz)	LOCATION	SPONSOR	(k watt)	TYPE OF TRANSMISSION
GBR	16.0	Rugby, England 52 22'N 01 11'W	British Post Office	1-5	CW
NAA	17.8	Cutler, Maine 44 39'N 67 17'W	USN	1,000	FSK for two hours followed by CW for one hour
NLK	18.6	Jim Creek, Wash. 48 12'N 121 55'W	USN	250	FSK continuous except five minutes before even hour lock key
WWVL	20.0	Boulder, Colorado 30 30'N 105 02'W	National Bureau of Stand.	>5	CW
NSS	21.4	Annapolis, Md. 38 59'N 76 27'W	USN	85	Time signals, 55 to 60th minutes of each hour. CW morse continuous
NWC	22.3	North West Cape, Australia 21 49'S 114 10'E	USN	1,000	CW first half hour of each even hour followed by FSK for 1 1/2 hour
NPM	23.4	Lualualei, Hawaii 21 25'N 158 90'W	USN	300	FSK continuous
NBA	13.0	Balboa, Canal Zone 09 04'N 79 39'W	USN	150	Time signals on CW morse from 55 to 60th minute every even hour except 2355 to 2400 UT. FSK teletype continuous at other times

Table I. Frequency-Stabilized VLF Stations

STATION	FREQ. (K Hz)	OFF PERIODS	REDUCED POWER OPERATION
NAA	17.8	1400 to 1800 UT each Friday	Each Wednesday and Thursday 1200 to 2000 UT transmitter operates 1/2 power
NLK	18.6	1000 to 1500 UT on the second Thursday of each month	
NSS	21.4	1300 to 1900 UT each Monday	
NWC	22.3	0500 to 1100 UT each Wednesday	
NPM	23.4	1700 to 0200 UT the first and third Monday each month	
NBA	24.0	1200 to 1800 UT each Wednesday	1200 to 2000 UT each Tuesday power reduced from 150 to 90 K watts

Table II. Reduced Power Periods

III. CHARACTERISTICS OF VLF PROPAGATION AFFECTING THE PROPOSED NAVIGATIONAL SYSTEM

With respect to the proposed navigational system, there are three fundamental concepts concerning VLF propagation; these concepts are (1) the waveguide mode theory of propagation, (2) the development of the two possible reception zones, and (3) the explanation of the diurnal shift and the trapezoidal approximation thereto. Since an understanding of these three concepts is necessary for an overall comprehension of the navigational system each will subsequently be discussed in detail.

The waveguide mode theory of VLF propagation attempts to explain the phenomenon of relatively low signal path attenuation and constant or predictable phase delay by use of a simple mathematical model of the ionosphere. In this model the earth and the lowest layer of the ionosphere form two reflecting surfaces and comprise a virtual waveguide with a height of 70 Km during the day.[1,2] At night the lowest layer dissipates and the effective height of the ionosphere is increased by about 20 Km. The phase velocity of a certain mode of transmission for a given set of conditions can be determined from a solution of the mode

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[1]Budden, K. G., "The Waveguide Mode Theory of the Propagation of Very Low Frequency Radio Waves," in Proceedings of the Institute of Radio Engineers, vol. 45, no. 6, June 1957.

[2]Wait, J. R., Electromagnetic Waves in Stratified Media, The MacMillan Company, 1962.

equations as set forth by Wait[3] and Wait and Spies.[4] If the frequency of transmission remains constant, the height of the ionosphere has a large effect on the phase velocity, lowering it with increasing height, with a resultant diurnal shift of phase delay of the received VLF signal.

In an excited waveguide whose dimensions are large with respect to a half-wavelength there will be more than one mode of transmission present. Such is the case in the earth-ionosphere waveguide. At short distances from the transmitting antenna many modes will be present, but at a distance of approximately 4000 Km or greater only the principal mode of interest (TM_1 mode) will be present. At this distance all higher order modes will have been attenuated and will be small enough in amplitude so as to be neglected.[5] This, then, limits the zone of reception to all positions located at a distance of at least 4000 Km or more from the station of interest.

An accurate prediction of the diurnal phase shift is essential if errors in phase delay, when the signal path is composed of segments in both daylight and darkness, are to be accounted for. The daily relative phase change can be

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[3] Ibid.

[4] Wait, J. R. and Spies, K. P., "Characteristics of the Earth-Ionosphere Waveguide for VLF Radio Waves," in National Bureau of Standards Technical Note 300, 30 December 1964.

[5] Blackhand, W. T., Propagation of Radio Waves at Frequencies Below 300 KHz, The MacMillan Company, 1964.

approximated by a trapezoid as shown in Figure 2, and the value of Δt can be computed from the following formula developed by Wait.[6]

$\Delta t = \frac{D}{0.3} \left(\frac{c}{v_n} - \frac{c}{v_d}\right)$ microseconds, where D is the distance to the transmitting station in Km, v_n and v_d are the night and day phase velocities in m/sec, and c is the speed of light in free space. This formula has been further refined to the following: $\Delta t = D \cdot k_v$, where D is as defined earlier and values of k_v for various frequencies have been computed.[7] Figure 2 represents an idealized example of a 24 hour plot of the phase of the received signal at a receiver located to the west of the transmitter. The segment E to A indicates the phase of the received signal during the period of time when the entire path is in daylight. Point A represents sunset at an altitude of 70 Km at the transmitter site, the received phase changes linearly until point B which represents sunset at the same altitude at the receiver. Segment B to C indicates the phase of the received signal during the time the propagation path is in total darkness. Point C represents sunrise at altitude at the transmitter and the phase again changes linearly to point D, which is the time

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[6]Wait, J. R., "The Mode Theory of VLF Ionospheric Propagation for Finite Ground Conductivity," in Proceedings of the Institute of Radio Engineers, vol. 45, no. 6, June 1957.

[7]Lake, LCDR. R. D., "An Investigation Into the Use of Very Low Frequency Transmissions for Ship Navigation," in Unpublished Master's Thesis, U.S. Naval Postgraduate School, Monterey, California, 1965, p. 13.

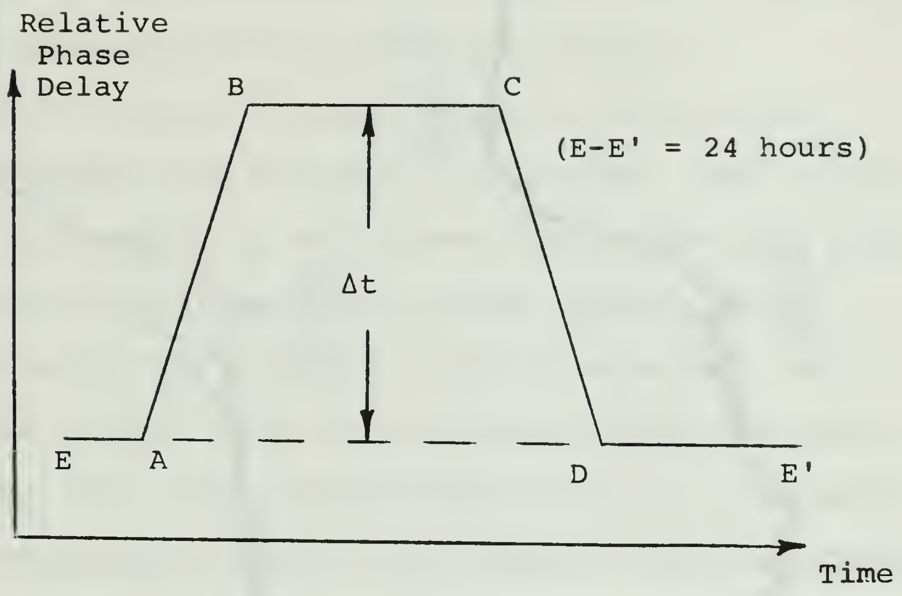

Figure 2. Diurnal Phase Shift

of sunrise at altitude at the receiver. The phase of the received signal is now identified with its previous value and maintains its daylight value to point E'. During the next 24 hour period this pattern will repeat.[8]

Figure 3 represents a part of two recordings of NBS station WWVL made at Monterey, California, over a 48 hour period. The actual positions of sunset and sunrise at altitude are not as distinct as the trapezoidal approximation, but are distinguishable.

An additional problem caused by the very long VLF propagation paths is the contamination of the short path signal by the long-way-around-the-world signal. This factor

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[8] Ibid., p.4.

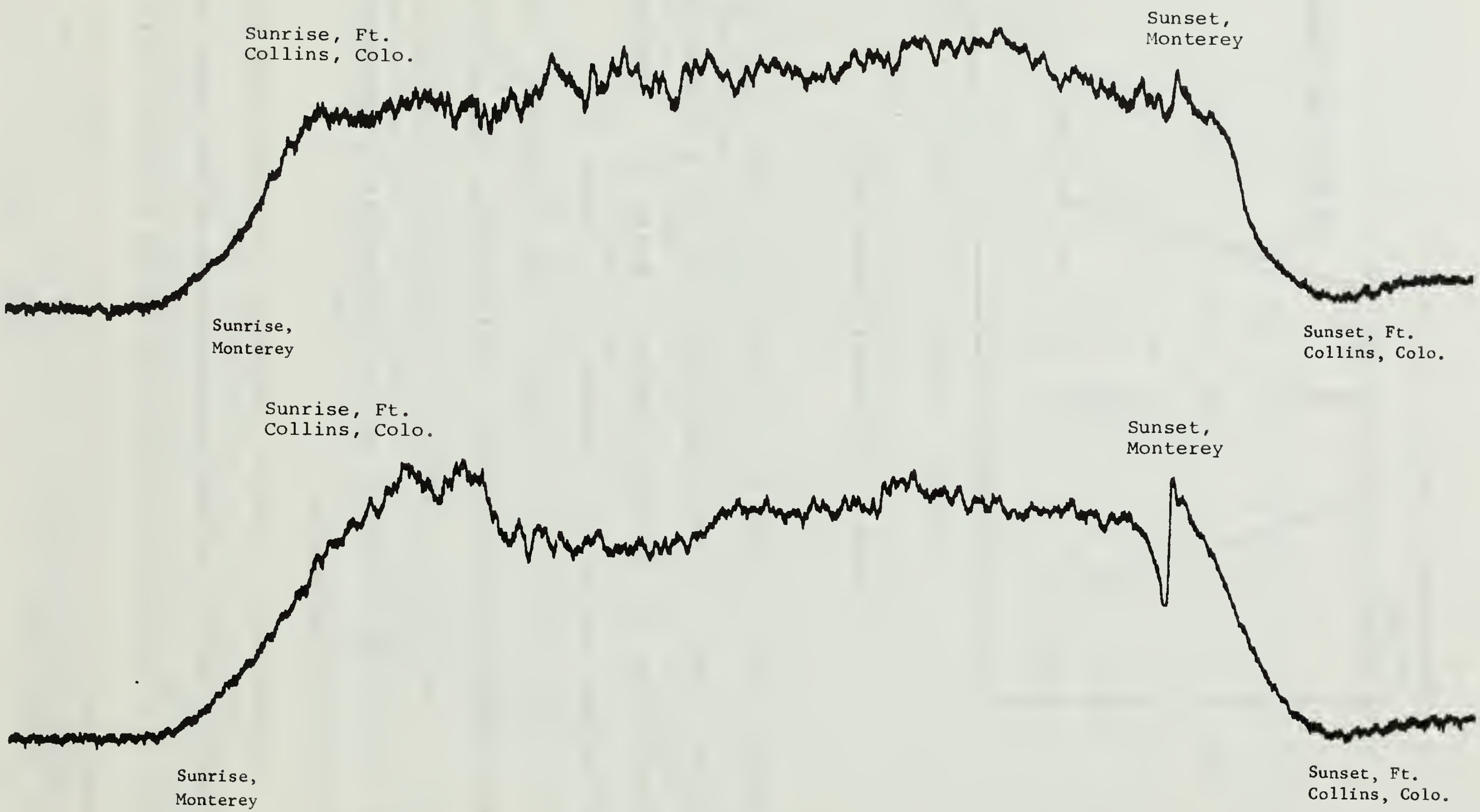

Figure 3. Diurnal Phase Shift Recordings

may be minimized by the use of an antenna with a cardiod shaped radiation pattern, as noted in Section I.

For maximum system accuracy numerous second order effects of propagation should be considered. Such factors as signal attenuation by paths over land or ice, and phase velocity pertubations caused by slight changes in the ionosphere height contribute to overall accuracy. Such second order effects will not be considered in this work.

To summarize, the waveguide mode theory of propagation sets up a mathematical model which permits the calculation of the daily phase change, and at the same time this model limits the use of a particular transmitting station to a geographical area which is at least 4000 Km distance from the station. Observed measurements of the electric field within the earth-ionosphere waveguide indicate that the mathematical model described can be used to approximate the actual physical case.[9] The restriction imposed by the zones of reception is not as severe as it would seem due to the world-wide coverage of transmitting stations, as depicted in Figure 1.

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[9] McKay, LT. J. D. and Preston, LT. G. L., "An Investigation of Factors which Degrade Phase Accuracy in a VLF Relative Navigational System," in Unpublished Master's Thesis, Naval Postgraduate School, Monterey, California, 1966, pp. 12-18.

IV. FREQUENCY STANDARDS AND VLF PHASE TRACKING RECEIVERS

As outlined in Section 1, the three major components of the proposed relative navigational system are the frequency-stabilized transmitting stations, a receiving antenna with an associated VLF phase tracking receiver, and an accurate local frequency standard. The antenna system as developed will be thoroughly discussed in succeeding sections, while the types and locations of the transmitting stations has already been covered. The remaining components, consisting of the frequency standard and VLF phase tracking receivers, will be examined in this section.

Frequency standards may be generally classified as either primary or secondary standards. A primary frequency standard establishes a frequency which is well defined without reference to any external standard. Secondary frequency standards are those which must occasionally be compared to an accepted source, such as a primary standard. Examples of primary standards are the hydrogen maser and cesium beam standards. These atomic resonance standards use quantum mechanical effects in the energy states of matter, particularly transitions between states separated by energies corresponding to microwave frequencies. Transitions having properties well suited to standards use occur in atoms of cesium, rubidium, thallium, and hydrogen. Considerable attention has been directed to three devices: the cesium atomic beam, the rubidium gas cell, and the hydrogen maser.

The cesium and rubidium devices utilize passive atomic resonators to steer conventional oscillators, usually of the quartz crystal types, via feedback control circuits. The hydrogen maser, an active device, derives its signal from stimulated emission of microwave energy amplified by electronic means to a useful power level.[1] The hydrogen maser is potentially capable of extremely high stability, and existing units have reached stabilities to parts in 10^{13} over periods of months,[2] while cesium beam tubes exhibit frequency pertubations so small that independently constructed tubes compare to within a few parts in 10^{12}.

Secondary frequency standards may consist of quartz crystal oscillators or rubidium vapor standards. Although the rubidium vapor standard is classified as a secondary standard, its basic frequency is derived from a high quality quartz crystal oscillator, whose frequency is stabilized by a passive resonance cell filled with rubidium and an inert buffer gas. The operation of the resonance cell is based on an optical pumping principle.[3]

The fundamentals of basic quartz crystal oscillators

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[1] Frequency and Time Standards, Application Note #52, Hewlett Packard Company, Palo Alto, California, 1965, p.2-1.

[2] Frequency, 2,4, July-August 1964, p.33.

[3] McKay, LT. J. D. and Preston, LT. G. L., "An Investigation of Factors Which Degrade Phase Accuracy in a VLF Relative Navigational System," in Unpublished Master's Thesis, U.S. Naval Postgraduate School, Monterey, California, 1966, p. 41.

are covered in numerous texts,[4] while a detailed description of a high quality quartz crystal oscillator may be found in reference 8. State-of-the-art characteristics for rubidium vapor standards include an RMS deviation from the mean of 5 parts in 10^{12} for a one-day averaging period, and a systematic drift of less than 3 parts in 10^{11} per month.[5] The long term stability of quartz crystal oscillators is conservatively rated at 5 parts in 10^{11} per day.[6]

The U. S. Navy sponsored VLF stations, discussed in Section II, are being controlled by the U. S. Naval Observatory (USNO) to within a part in 10^{11} of their assigned frequencies by comparison to the USNO master clock. This clock is in turn compared with the National Bureau of Standards (NBS) maintained U.S. Frequency Standard (USFS) located at Boulder, Colorado. As reported in Appendix III, on 28 October 1968 at 2340 UT the USNO master clock was measured to be 0.7 microseconds ahead of the NBS clock. As of the latest measurement, made on 22 August 1968 at 1430 UT, the USNO master clock was 3.7 microseconds behind the NBS clock.

A VLF phase tracking receiver is a special type of receiver in which the phase difference between the local

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[4]Terman, F. E., Electronic and Radio Engineering, McGraw-Hill, New York, 1955.

[5]McCoubrey, A. O., "A Survey of Atomic Standards," in Proc. IEEE, vol. 54, no. 2, February 1966, pp. 116-135.

[6]Frequency and Time Standards, op. cit., p.2-3.

frequency standard and the received signal is measured. An example of such a receiver is the TRACOR model 599G. This receiver continuously displays the relative time difference between the local standard and the received signal on a VEEDER-ROOT digital counter, located on the receiver's front panel, recording changes in phase as small as 0.1 microseconds. The operation of this receiver is treated in detail in references 1 and 2 and will not be repeated here.

Since the heart of the proposed navigational system is an accurate phase comparison, the system can be no better than its least accurate component. In most cases this component will be the local frequency standard. While the cost of equipment is an overriding factor in most systems, Stanbrough and Keily considered that a combination of two TRACOR 599 receivers and a Sultzer model D2.5 frequency standard (high quality quartz crystal oscillator) with a standby power supply is the best commercially available equipment, and would cost upwards of $13,000. A single receiver modified to receive several VLF stations on a time sharing basis would reduce the cost of the system to less than $10,000. It must be emphasized that this is a cost estimate for the year 1964. Subsequent equipment developments and larger volume procurement should substantially reduce the cost of such a system.

V. ANTENNAS

The antenna system, which is composed of two crossed loops and a whip antenna combined with a goniometer, will be developed in the following four sections. Section V examines the basic single loop antenna and its radiation pattern and explains how such a pattern may be modified by an additional sense antenna to produce a cardiod shaped pattern. In Section VI, the theory of operation of an inductive type goniometer is explained, and the application of this goniometer to a single loop antenna is examined. Section VII considers the combination of two loops into a single crossed loop antenna with the output applied to a goniometer, and develops the concept of multi-station reception by turning the goniometer. The final section will combine the crossed loops, goniometer, and whip sense antenna to achieve the final antenna system in which a multi-station, electronically rotatable, cardiod shaped radiation pattern has been evolved.

When referring to "antenna patterns" some distinction must be made as to what parameters are being measured. Unless otherwise noted, "antenna pattern" will refer to a measurement of field strength versus polar angle.

The loop antenna has been used for many years for both reception and direction finding. A loop may be either circular, rectangular, triangular, diamond-shaped or of some other configuration. As applied to the VLF spectrum, all

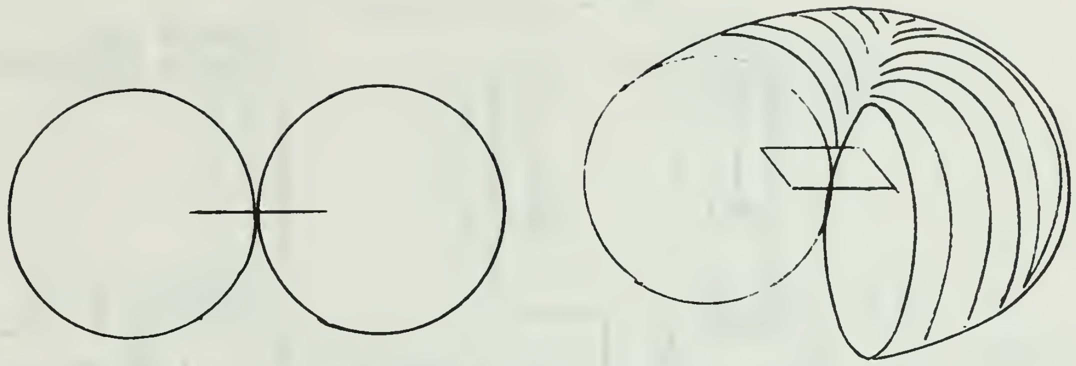

Figure 4. Loop Radiation Pattern

loops must be considered to have a diameter which is small when compared to a wavelength, and as such it can be shown that the far fields of circular and square loops of the same area are identical.[1] A vertical loop antenna produces a polar radiation pattern in a plane at right angles to the antenna of the familiar figure eight (tangent circles) shape, as shown in both plan view and isometric projection in Figure 4.

For purposes of direction finding the station desired should be located in the pattern null position, since the null position is much sharper than the broad maximum. For purposes of VLF reception the loop would be oriented to the

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[1]Kraus, J. D., Antennas, McGraw-Hill, New York, 1950, pp. 170-171.

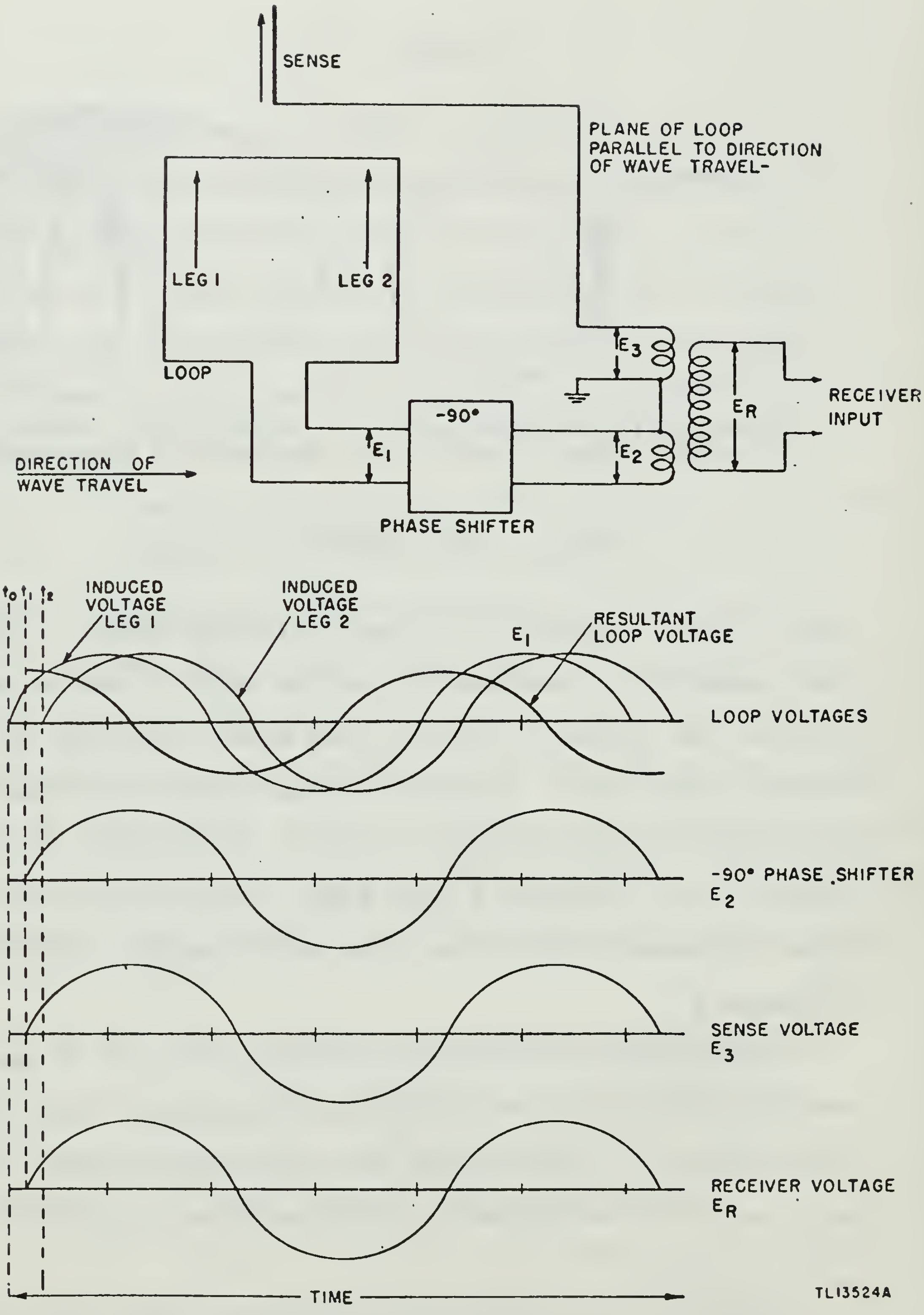

Figure 5. Loop and sense antenna system, relationship of voltages

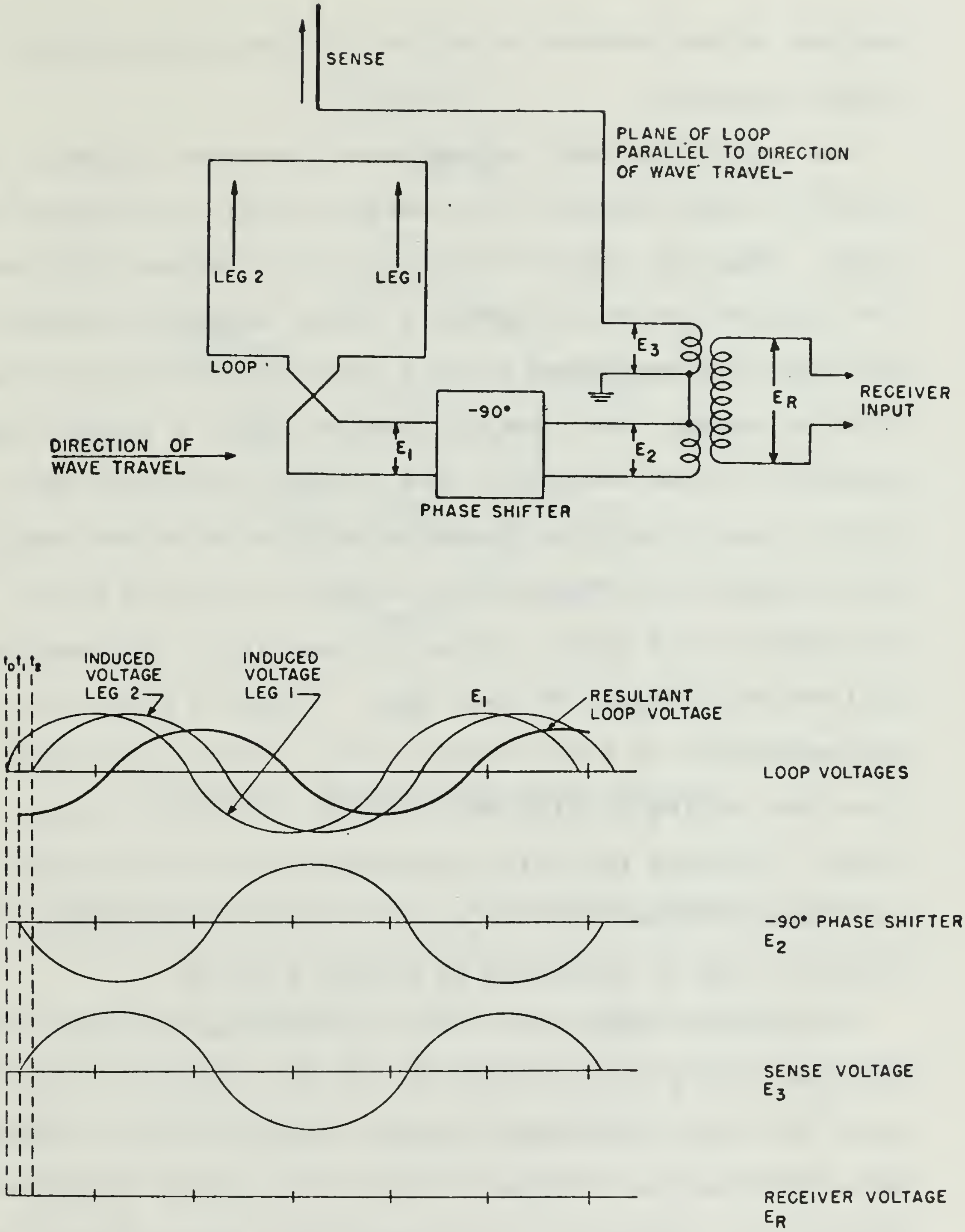

Figure 6. Relationship of voltages in loop and sense antenna system when loop has been rotated 180° from position of Figure 5

maximum of the pattern to achieve the greatest received signal strength.

An omnidirectional whip antenna produces a pattern in a plane at right angles to the antenna which is circular in shape. When the output of the whip is combined with that of the loop, as shown in Figures 5 and 6, and after proper phase shifting, the resultant antenna radiation pattern will be cardiod shaped. The time diagram of Figure 5 gives a representation of the voltage in leg 2 being subtracted from that in leg 1, and distinguishes this value as the resultant loop voltage (E_1). When this voltage is shifted by 90° (E_2) and added to the sense antenna voltage (E_3), the resultant will be the receiver voltage (E_R). Figure 6 gives a similar representation of the voltage in leg 1 being subtracted from that of leg 2, with the receiver voltage as shown. Figure 7 depicts the polar representation of the cardiod amplitude pattern with two specific points, developed in Figures 5 and 6, indicated as points A and B.

The phasor combination of loop and sense antennas may be conveniently accomplished by use of a TRACOR CARDIOD UNIT model 611, which has been designed for use with the TRACOR model 599G series VLF phase tracking receivers discussed in Section IV. This unit, as schematically represented in Appendix D, is able to accomplish the necessary fine adjustments of phase and amplitude to achieve the cardiod pattern. In practice a peak to null ratio of approximately 30 db has

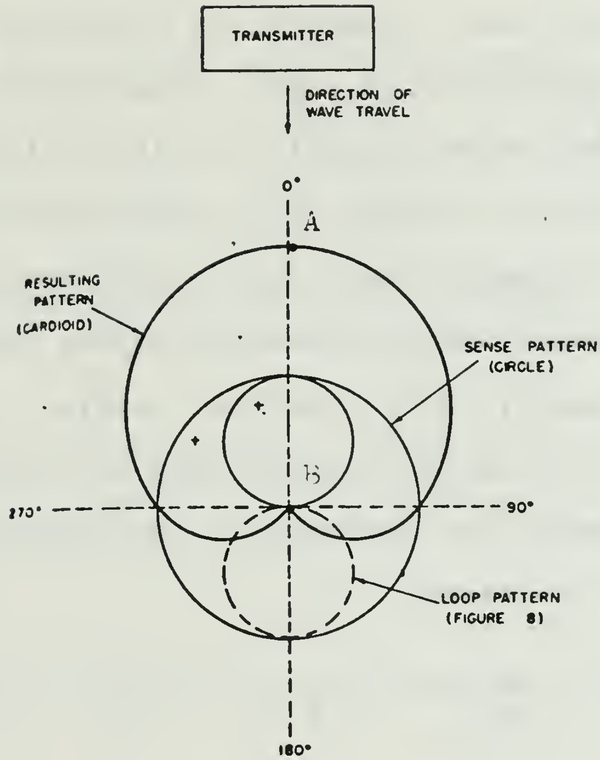

Figure 7. Cardiod Amplitude Pattern

been realized with this unit. The antenna pattern is now able to discriminate against signals arriving at the antenna from reciprocal directions, hence the elimination of the long-way-around-the-world contamination discussed in Section I, can be accomplished. It is now necessary only to keep the cardiod antenna peak oriented towards the direction of the shortest great circle path to the transmitting station of interest.

The most remarkable feature of the cardiod shaped radiation pattern, excluding the aforementioned front-to-back signal discrimination, is the fact that the phase of the pattern remains nearly constant for approximately 100° on either side of the cardiod peak. Preston and McKay analytically and experimentally formulated the pattern as shown in Figure 8. The fact that the phase of a received signal remains constant over such a wide angular separation eases the necessity of continually keeping the cardiod peak oriented at exactly the transmitter bearing. This tolerance in orientation, together with the signal discrimination feature, is one of the fundamental concepts upon which this antenna system is based.

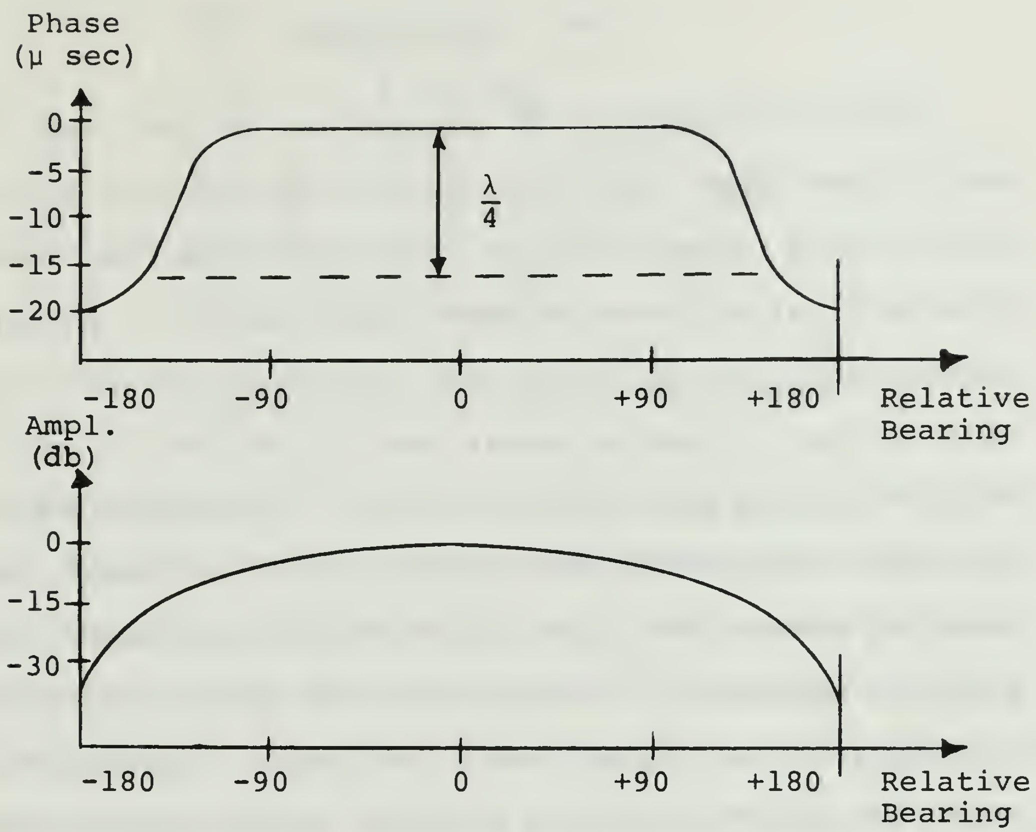

Figure 8. Cardiod Phase and Amplitude Patterns

VI. GONIOMETERS

The term goniometer is applied to a device used to couple two or more input circuits (usually connected to antennas) to an output circuit (usually connected to a radio receiver). In electrical engineering work this coupling is normally accomplished through the mutual inductance between two coils. This is done in such a manner that the degree of coupling varies with the rotation of a shaft. The coupling between one input circuit and the output circuit increases, while the coupling between the other input circuit decreases. When properly connected, a well constructed goniometer provides an output, at each position of its shaft, identical to that which would be produced by a single figure-eight-pattern antenna oriented to the corresponding position. Thus the goniometer provides an equivalent for rotation of the antenna and makes it possible to use large fixed antenna systems which would, in themselves, be too bulky to rotate.[1]

The most common form of goniometer, particularly at lower frequencies, is the inductive type which usually consists of two fixed windings, arranged at right angles to each other, and inclosing a third winding which is rotatable by means of a shaft. Figure 9 shows the basic goniometer circuit.

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[1]Radio Direction Finding, War Department Technical Manual, Washington, D.C., 1947, p. 61.

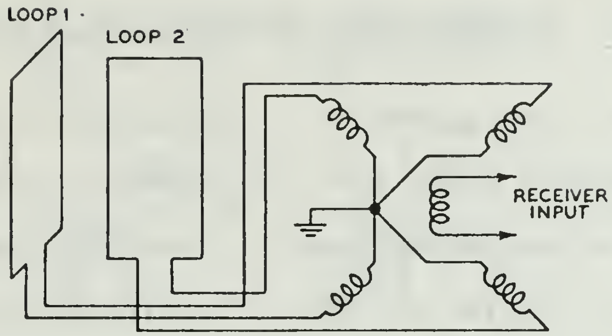

Figure 9. Basic Goniometer Circuit

When the two fixed windings are connected to two identical antennas having figure-eight patterns and arranged at right angles, the magnetic field within the goniometer will have a direction, with respect to the fixed windings, corresponding to the direction of arrival of the signal with respect to the fixed windings. As the internal windings, or search coil, of the goniometer is rotated, its output will vary from maximum to minimum twice per revolution exactly as would the output of one of the antennas if it were rotatable.[2] This sampling concept is adapted to a crossed loop antenna, and fully developed in the next section.

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[2] Ibid., p. 61.

VII. CROSSED LOOP ANTENNAS AND A GONIOMETER

When two loop antennas at right angles are combined into a single crossed loop, and the output of each loop is applied to a goniometer stator, they will exhibit a radiation pattern similar to that of a single loop. With such an arrangement the loops are now fixed while the rotor of the goniometer is turned to create the desired figure-eight pattern. Figure 10 indicates the goniometer positions for maximum and minimum signal strengths corresponding to 5 directions of signal arrival with respect to the fixed antenna. Loops 1 and 2 are connected to coils 1 and 2 respectively, and the maximum signal is obtained when the rotor is parallel to the coil of the loop for cases a and b, or parallel to the combination of the coils for cases c, d, and e. The minimum signal will be obtained, as shown, at a 90° location from the maximum.

At intermediate positions between maximum and minimum the rotor output will generate the values of a figure-eight pattern, as indicated in the last column of Figure 10. The antenna system now has the capability of receiving any number of separate stations, each station requiring its own VLF phase tracking receiver, but of only receiving one station maximum at a time. If the reception of more than one station maximum is desired, a goniometer and VLF phase tracking receiver for each station would have to be connected to the one crossed loop antenna, and each goniometer

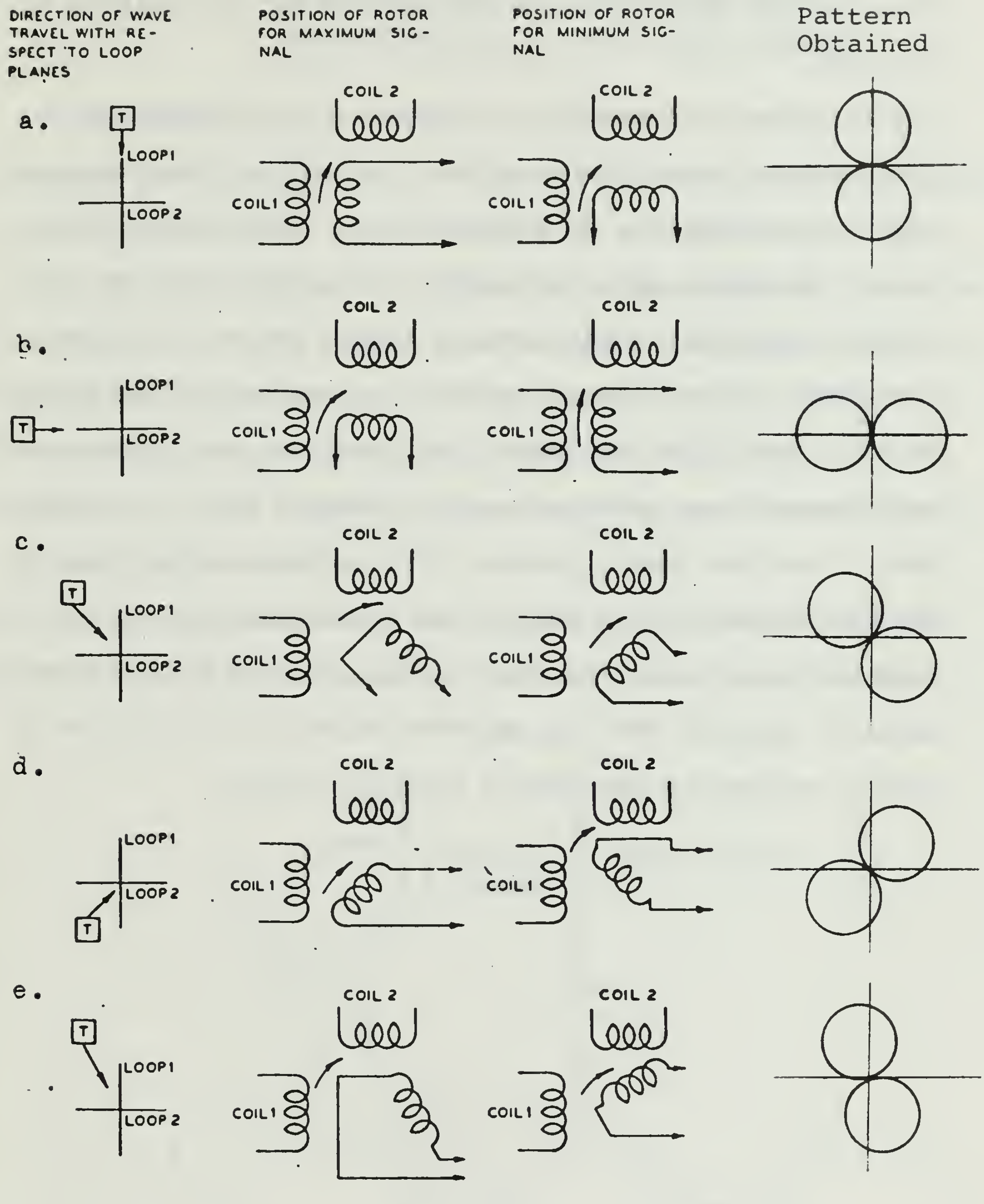

Figure 10. Goniometer system and directional characteristics

rotor turned separately to the maximum of the station of interest.

One fixed crossed loop antenna is now sufficient to simultaneously receive more than one transmitting station, with the limitations on the number of stations to be received dependent upon the number of goniometers and receivers available. The antenna system as has now been developed, if modified to achieve a cardiod shaped radiation pattern, would be sufficient for navigational purposes if the crossed loop antennas were to remain fixed in azimuth. Such is not the case, however, for antennas which are rigidly attached to a ship. The following section will tie together many ideas thus far developed, and will devise a means to correct for the apparent change in direction of signal arrival as the ship's heading changes.

VIII. CROSSED LOOP ANTENNA COMBINED WITH A GONIOMETER AND A WHIP SENSE ANTENNA

The radiation pattern of the output of a crossed loop antenna and a goniometer is the figure-eight shape associated with a single loop. The addition of a whip sense antenna and a TRACOR cardiod unit (for fine adjustments of phase and amplitude) to this output will convert the figure-eight to a cardiod shaped pattern. This conversion is similar to that developed for the single loop and whip antenna in Section V. The complete antenna system as now developed is shown in Figure 11.

The antenna now has the capability of producing a cardiod shaped radiation pattern with any station of interest

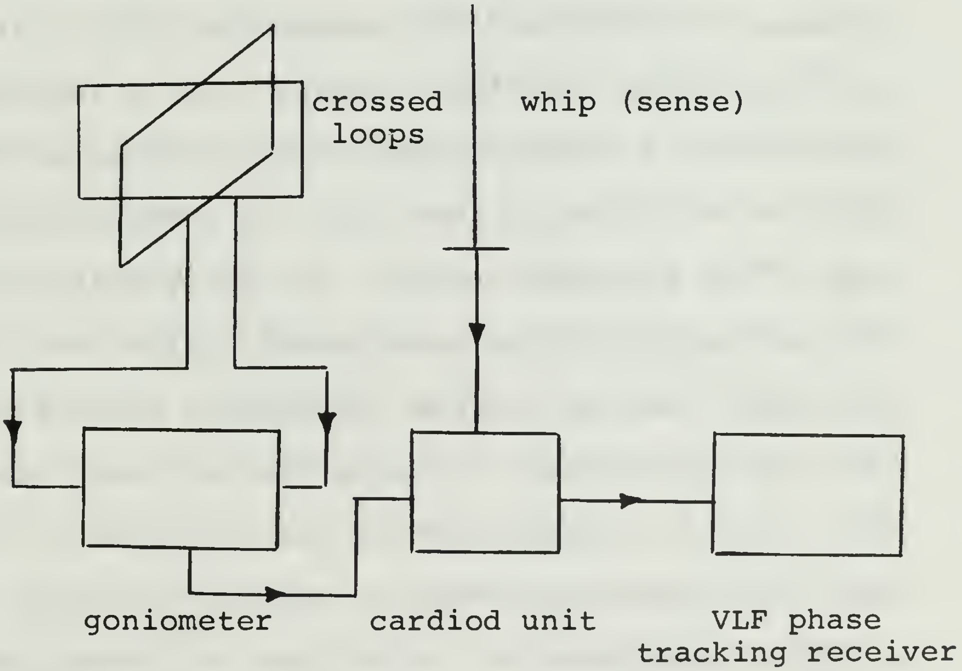

Figure 11. Complete Antenna System

by means of a rotation of the rotor of the goniometer which is connected to the fixed crossed loop antenna. As mentioned earlier, for each station tracked a separate goniometer, cardiod unit, and VLF phase tracking receiver is required, but one crossed loop and whip antenna may be used with the individual goniometers.

In order to correct for the change in azimuth angle of a crossed loop antenna caused by a ship's course change, a means must be devised to either reposition the large antenna or else reposition the goniometer rotor. Due to the size and weight considerations of an antenna, the azimuth stabilization of the goniometer rotor is the easier solution to the problem. Towards this end a means has been developed whereby an output from the ship's gyrocompass is used to continually reposition the goniometer rotor. As the platform upon which the fixed crossed loop is rotated, a servo signal which is obtained from the gyrocompass alters the position of the goniometer rotor in a direction opposite to that of the platform motion. In this way the maximum of the cardiod pattern is continuously maintained on a true geographic bearing towards the station being tracked. If more than one station is being tracked, each goniometer rotor must be repositioned by the same amount. A simple gear train arrangement may be employed to carry out this multiple repositioning. This gives the added advantage that only one servo signal is required. This feature is considered worthwhile since many ship gyrocompass installations provide for only a limited number of remote indicators.

As an illustration of how such a stabilized goniometer would operate, consider the following example. Assume that a ship with the antenna system of Figure 11 is initially alongside a pier with a ship's heading 000° T. The particular station to be tracked is located to the northeast at a distance of approximately 5000 Km. While still alongside the pier the goniometer rotor is positioned to receive the station on a bearing of 045° T, and fine adjustments are made with the cardiod unit to establish the cardiod pattern peak on the proper bearing. With the pattern thus obtained continuous tracking of the station is begun. The goniometer rotor is now locked to an azimuth stabilized compass card, but since the ship's heading is stationary the rotor position remains constant.

As the ship gets underway and changes course, the compass card to which the goniometer rotor is locked will be continuously repositioned so as to maintain its correct heading with respect to the earth. Since the rotor is locked to this card it will also be maintained on a true bearing of 045° T. Figure 12 shows this orientation of the loops and compass card for the moored situation, as well as three different underway conditions. In all four cases the goniometer rotor, and resultant cardiod pattern, are properly oriented towards the transmitting station. As the ship travels away from the original location, particularly on a course normal to the bearing of the

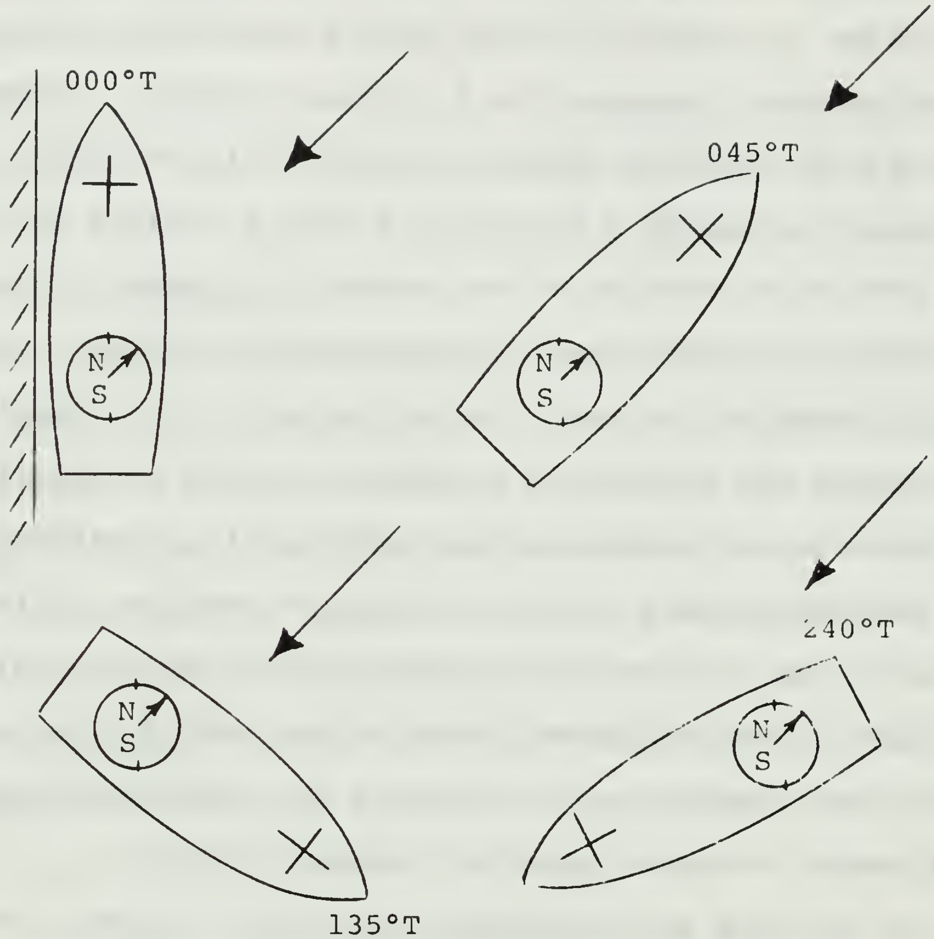

Figure 12. Stabilized Rotor Orientations

transmitting station, the true bearing to the station will change. Some adjustments of the rotor direction might now be necessary to keep the cardiod peak oriented towards the transmitting station. Fortunately, due to the insensitivity of the cardiod pattern, as mentioned earlier, corrections need only be made when the change in bearing becomes large.

With this final adaptation the antenna system now possesses the necessary features to continuously track a

VLF phase-stabilized station with the required cardiod pattern from a moving platform. The relative change of the phase of the received signal is now a measurement of the distance traveled.

IX. FABRICATION OF THE SYSTEM'S CROSSED LOOP ANTENNA

The antenna constructed for this navigational system consists of two circular loops at right angles and a whip located at the intersection of the two loops. Figure 13 shows the overall antenna arrangement. A junction box at the

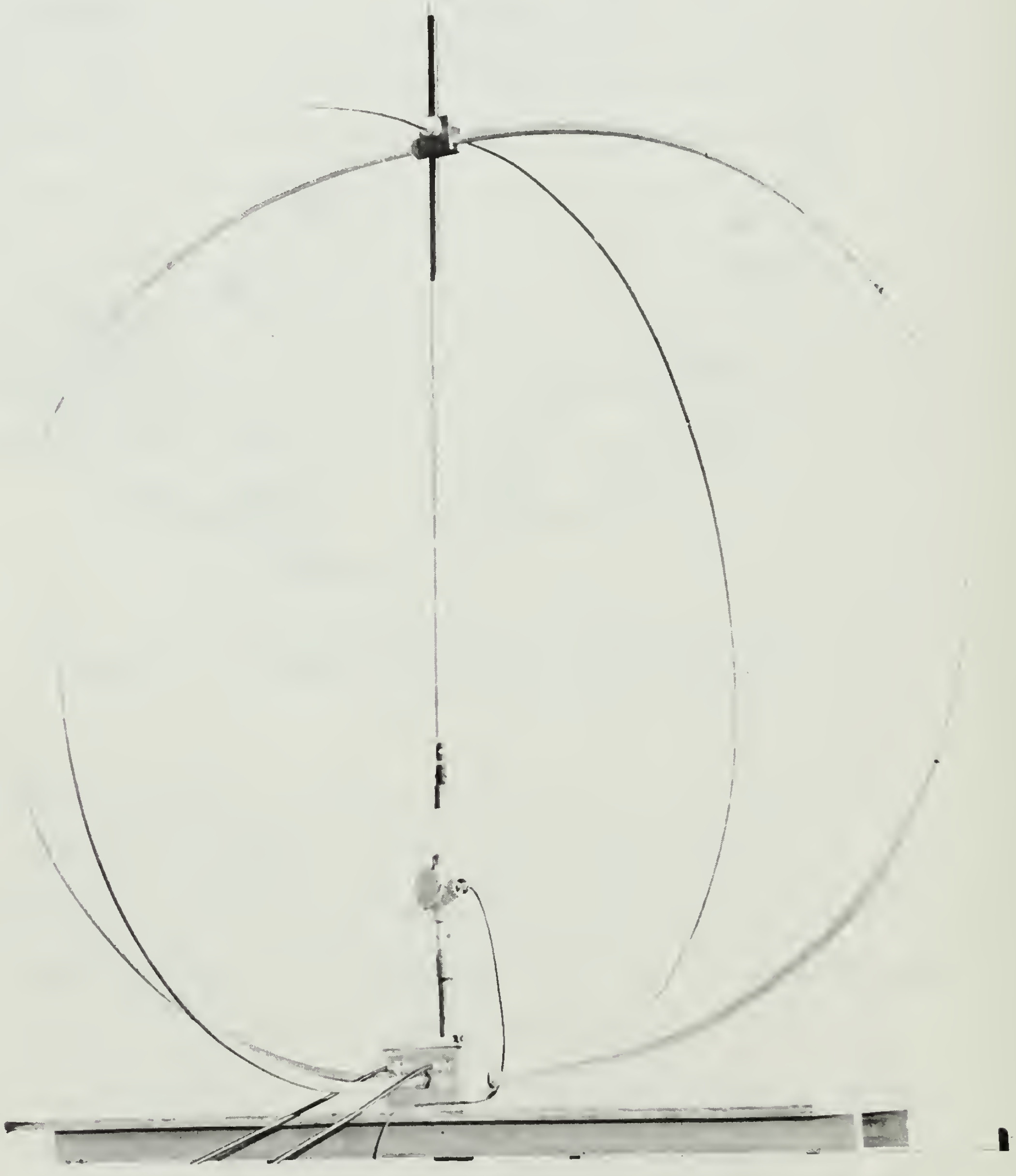

Figure 13. Crossed Loop and Whip Antenna

base of the loops provides a foundation for the mounting of the whip, and also serves as a housing for the loop tuning circuits.

The loop's dimensions are 6 feet in diameter and each loop contains 52 turns of 22 AWG thermo plastic insulated 10 X 30 hookup wire (MIL SPEC. W-768). The turns of wire are wound within a 1 inch (O.D.) aluminum tubing which serves as both a framework for the wire as well as an electrostatic shield. An insulating connector at the top of the two loops, shown clearly in Figure 13, provides the electrical open circuit for the shield. Shielding of each loop is necessary to ensure that all parts of the loop will always have the same capacitance to ground irrespective of the loop orientation in relation to neighboring objects.[1]

The whip portion of the antenna is a TRACOR model 599-800 vertical antenna designed for reception of signals in the 10 KHz to 30 KHz frequency range. This antenna is designed to be used with the TRACOR model 599 or other VLF receivers. The whip is constructed of three telescoping sections of cadmium plated steel and has a fully extended length of 20 feet. The terminal output impedance of this antenna is 50 ohms.

In order to achieve a balanced loop output each loop is connected to a tuning circuit, a diagram of which is shown

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[1]Terman, F. E., Electronic and Radio Engineering, McGraw-Hill, New York, 1955, p. 1049.

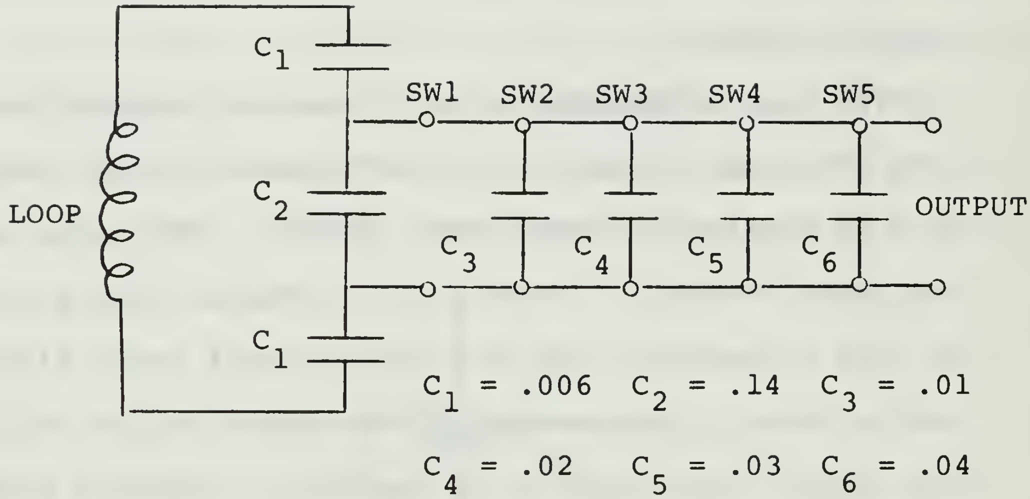

Figure 14. Loop Tuning Circuit

in Figure 14. The inductance of each loop was measured with a General Radio type 1650-A impedance bridge and found to be 20 millihenries. At a frequency of 20 KHz this inductance would need to be shunted by a capacitance of 3180 picofarads to form a resonant circuit. By using a combination of three capacitors in series, the resultant shunt capacitance is approximately that which is required (2860 picofarads for one loop, and 2910 picofarads for the other loop). If the loop output is obtained across the capacitor C_2 (0.14 microfarads) the terminal output impedance at 20 KHz will be 56 ohms.

As shown in Figure 14, the addition of a 5 position switch and trimmer capacitors (C_3, C_4, C_5, and C_6) permits fine adjustment of antenna tuning. Table III indicates the measured values of output capacitances at all switch positions.

The balanced outputs of the crossed loops are connected to each goniometer stator by means of shielded TWINEX cable, and the whip sense antenna is connected to the cardiod unit. The wiring arrangement is shown in Figure 11.

TABLE III

Tuning Circuit Capacitances

	SW1	SW2	SW3	SW4	SW5
LOOP 1	.138	.147	.159	.168	.177
LOOP 2	.134	.142	.155	.163	.172
note: all values in microfarads					

X. FABRICATION OF AZIMUTH STABILIZATION CONSOLE

Goniometer rotor azimuth stabilization is required for a continuous tracking of a transmitting station from a moving platform. Two stabilized goniometers are needed to track two stations. The electro-mechanical method developed for such a stabilization is described in this section.

As previously mentioned in Section V, the orientation of the goniometer rotors can be accomplished by locking each rotor to a compass card. These compass cards are continuously repositioned by a gear train, which is controlled by a servo signal from the ship's gyrocompass. In this manner the goniometer rotors will be maintained on the correct station bearing regardless of the motion of the antenna platform. The goniometer stators and antenna may be considered as fixed to the platform, while the rotor may be thought of as fixed to the earth. Figure 12 of Section VIII illustrates this stabilization concept.

The actual mechanical arrangement that accomplishes this orientation feature is shown in Figure 15. Gear wheel C is driven by a servo motor which receives its signal from the ship's gyrocompass. The movement of gear C is coupled to the two compass cards by idler gears B and D. Two compass cards, which have been located directly above the two goniometers, are attached to gears A and E. The goniometer rotor shafts are shown as passing through an opening in the two compass cards, and are locked to the cards by means of adjustable

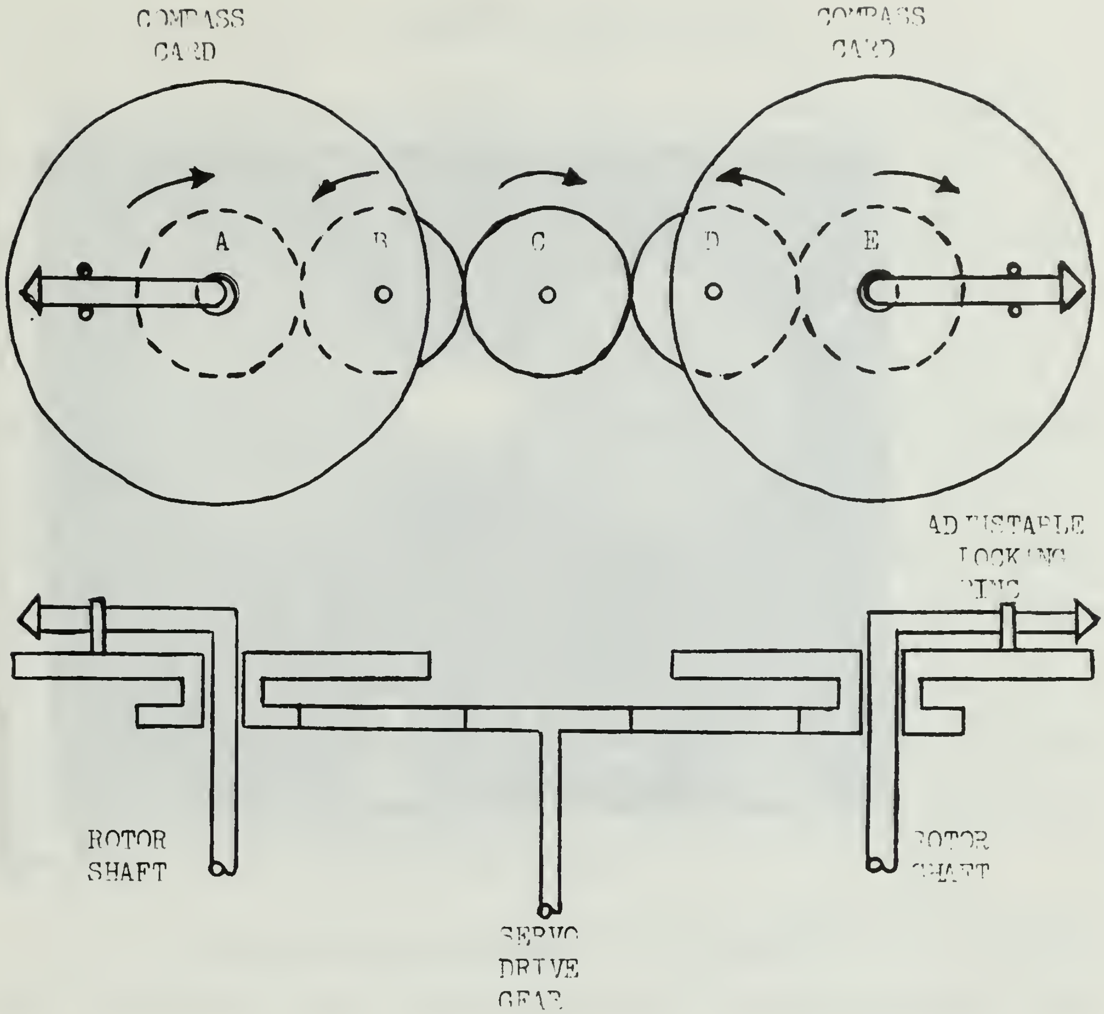

Figure 15. Goniometer Rotor Stabilization

pins. As the servo drive gear turns in response to a movement of the antenna platform, the compass cards and goniometer rotor follow the motion of the drive gear.

Figure 16 shows the front panel of the stabilization console just described. The three inputs required to this console are (a) 120 volt 400 cycle power from the ship's gyrocompass, (b) three stator connections (S1, S2, and S3) from the gyrocompass, and (c) 120 volt 60 cycle power from

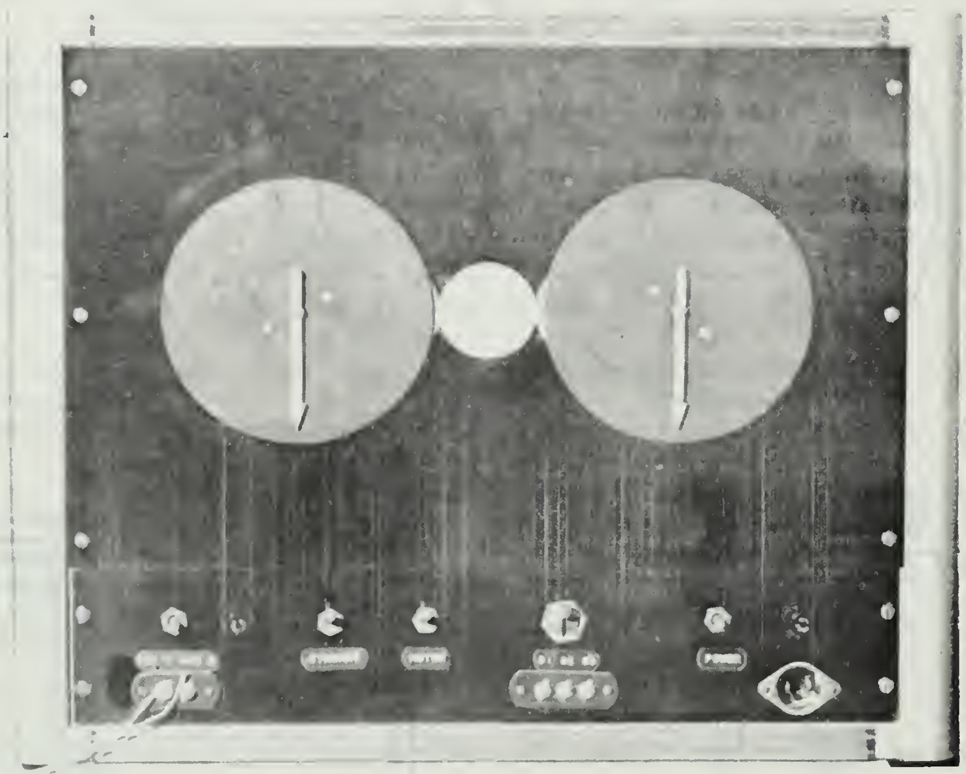

Figure 16. Stabilization Console

the ship's AC power supply. The two switches labelled SYNCHRO and MOTOR are not used for stabilization purposes, but provide a means of rotating the compass cards at a slow speed (1/5 RPM) to record antenna radiation patterns.

XI. ANTENNA SYSTEM TESTS

The loop/whip antenna unit and stabilization console was tested at the Naval Postgraduate School, Monterey, California, for a period of about three weeks during which time patterns of daily phase shift were plotted (Figure 3). The local frequency standard employed for the test was a Varian model V-4700 rubidium vapor standard. This secondary standard exhibited an RMS deviation from the mean of 1-2 parts in 10^{11} using an averaging period of one day.[1] Good daily phase shift plots were obtained with the signals from NAA at Cutler, Maine, NSS at Annapolis, Maryland, NPM at Lualualei, Hawaii, and NBA at the Canal Zone. The favorable results of these tests prompted a further test of the overall system from a moving platform.

During this testing period the only available platform for a shipboard test was a converted 63 foot air-sea rescue boat used at the Naval Postgraduate School as an oceanographic laboratory vessel. It was felt that the use of a small craft for a one day cruise on the Monterey Bay would provide a good approximation of a larger craft in the open ocean. In actuality, the platform motion generated by the rescue boat was more than sufficient for a motion test of the antenna system.

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[1]McKay, LT. J. D., and Preston, LT. G. L., "An Investigation of Factors which Degrade Phase Accuracy in a VLF Relative Navigational System," in Unpublished Master's Thesis, Naval Postgraduate School, Monterey, California,1966, p.45.

The antenna unit and stabilization console were temporarily installed on the rescue boat on 23-24 November 1968. For this underway test the frequency standard employed was an 0-471/U crystal controlled radio frequency oscillator. This oscillator was calibrated against a rubidium vapor standard and was conservatively rated as accurate to 1-2 parts in 10^{10}. After a 12 hour inport period of tracking NPM (Hawaii), the air-sea rescue boat got underway from the Monterey marina and headed on a northerly course towards Santa Cruz. For this test a tracking of only one station was contemplated. Rather than actually try to navigate, a test of the stabilization console and antenna unit, under actual conditions of ship's motion, was desired.

While the boat was backing and filling, and prior to leaving the Monterey breakwater, the stabilization system functioned as had been anticipated, maintaining a constant signal strength and constant phase difference. As the boat entered open waters and headed fair for Santa Cruz, the pitching and rolling motion of the deck increased to such an extent that the average deviation from the true vertical was about 15°, with occasional rolls of up to 25°. As mentioned earlier, this was considered as more than satisfactory for simulating platform motion. While on a steady course and speed the received signal phase variation was observed to change at a constant rate, and after a course reversal the variation changed with an equal rate but in the opposite direction. As a final check of the system's operation the boat was stopped dead in the water and, as was anticipated, the received phase and signal strength did not change for a period of 15 minutes. During this interval the motion of the boat was equal to, if not greater than, that described earlier.

Throughout the entire span of the underway test the signal strength varied less than 2 db even though considerable antenna motion existed. This was a most encouraging observation since the effect of a ship's pitch and yaw upon such an antenna had yet to be evaluated.

In summary, the underway test of the overall antenna system was considered satisfactory. Although no actual navigation was performed, the loop/whip antenna unit was given a most thorough motion test and the stabilization console functioned as designed.

XII. CONCLUSIONS AND RECOMMENDATIONS

This development of an antenna system, which is capable of being stabilized in azimuth, and at the same time providing a cardiod shaped radiation pattern, is a further step towards the proposed VLF relative navigational system discussed in Section 1. This paper has relied heavily upon the work of Preston and McKay, and the antenna system developed would not have been possible without the knowledge of the cardiod phase and amplitude patterns which they formulated.

Further testing of this system is suggested. The unavailability of a large vessel and time limitations permitted only one shipboard test. This test was considered satisfactory in that it indicated a workable overall system under shipboard conditions. Subsequent testing should be of an extended duration and should evaluate the multiple station tracking feature. With such testing a systematic procedure for navigation could be developed. Such a procedure might be based upon the sample navigational problems as presented by Lake, and Stanbrough and Keily.

APPENDIX A

Low Frequency Stations and Their Approximate Frequencies

FREQ (KHz)	CALL	LOCATION	REMARKS
7.428	FTH-42	Pontoise, France	Al
10.2		Trinidad	Omega
11.333		Aldra, Norway Haiku, Hawaii	Navigation
13.6		Forestport, New York	Spaced dashes
10.775	FTK-77	Pontoise, France	Al
13.873	FTN-87	Pontoise, France	Al
15.72			TV sweep frequencies
16.0	GBR	Rugby, England	Time ticks
16.2	RCC7	USSR	
16.8	FUB	Paris, France	Time and coded groups
17.4	NDT	Yosami, Japan	USN
17.8	NAA	Cutler, Maine	USN
18.0	NBA	Canal Zone	USN
18.0	FUB	Paris France	Time
18.6	NLK	Jim Creek, Wash.	USN
19.0	GQD	Anthorn, England	
19.6	GBZ	Criggen, Wales	
20.0	WWVL	Fort Collins, Colo.	Standard frequency
21.4	NSS	Annapolis, Md.	USN
23.0	NKA	Asmara, Ethopia	USN
24.0	NBA	Canal Zone	USN

26.1	NPM	Lualualei, Hawaii	USN
50.0	OMA	Podebrady, Czechoslovakia	Standard frequency
60.0	WWVB	Fort Collins, Colo.	Standard frequency
60.0	MSF	Rugby, England	Standard frequency
75.0	HBG	Prangins, Switz.	
89.0	NSS	Annapolis, Md.	USN
91.15	FTA-91	St. Andre de Corcy, France	A1
100.0	ZUO	Johannesburg, Rep. of S. Africa	
100.0	RWM-RES	Moscow, USSR	
110.0	CKN	Vancouver, B.C.	
113.0	WSL	New York	Press to ships at 0300 GMT, 25 WPM
114.5	CFH	Halifax, N.S.	
114.95	NPG	San Francisco	USN
115.3	CFH	Halifax, N.S.	
121.95	NSS	Annapolis, Md.	USN
129.95	GKU	England	
131.05	NPM	Lualualei, Hawaii	USN
131.8	FYA-31	Paris, France	Weather, facsimile
133.0	CFH	Halifax, N.S.	
136.5	FYA-36	Paris, France	Weather, facsimile
147.5	WCC	Chatham, Mass.	Press to ships at 0300 GMT at 26 WPM
162.0	NSS	Annapolis, Md.	USN
164.0		Radio Luxembourg	A3

200.0	BBC	Droitwich, England	
233.0		Radio Luxembourg	A3

The above frequencies and station designations were obtained from the October 1968 edition of QST and Hewlett-Packard application note #52, and are subject to revision.

U. S. NAVAL OBSERVATORY
WASHINGTON, D.C. 20390

27 September 1968
(Supersedes T. S. Ann. of 15 March 1968)

TIME SERVICE ANNOUNCEMENT, SERIES 3

NO. 6

SCHEDULE OF TIME AND FREQUENCY TRANSMISSIONS
ON VLF FROM U. S. NAVAL RADIO STATIONS

1. The following schedule is in effect:

Station	Location	Frequency (kHz)*	Radiated Power (kw)	Maintenance	Special Transmissions
NAA	Cutler, Maine 44°39'N 67°17'W	17.80	1,000 (1)	1400 to 1800 UT each Friday	FSK for two hours followed by CW for one hour. Phase stable on 17.80 but not on 17.85 kHz.*
NBA	Balboa, Canal Zone 09°04'N 79°39'W	24.00	150 (2)	1200 to 1800 UT each Wednesday	Time signals on CW Morse from 55 to 60th minute every even hour except 2355 to 2400 UT. FSK teletype continuous at other times. Phase stable on 24.00 but not on 24.05 kHz.* (4)
NLK	Jim Creek, Wash. 48°12'N 121°55'W	18.60	250	1000 to 1500 UT on second Thursday of each month	FSK continuous except five minutes before even hour lock key. Phase stable on 18.60 but not on 18.65 kHz.*
NPM	Lualualei, Hawaii 21°25'N 158°09'W	23.40	300	1700 to 0200 UT 1st & 3rd Monday	FSK continuous. Phase stable on 23.40 but not on 23.45 kHz.* (4)
NSS	Annapolis, Md. 38°59'N 76°27'W	21.40	85	1300 to 1900 UT each Monday	Time signals, 55 to 60th minute of each hour. CW Morse continuous. Phase stable.
NWC	North West Cape, Australia 21°49'S 114°10'E	22.30	1,000	0500 to 1100 UT each Wednesday	FSK and CW. See note (3).

Station	Location	Frequency (kHz)*	Estimated Radiated Power (kw)	Maintenance
Omega Norway Ω/N	Aldra, Norway 66°25'15"N, 13°09'10"E	10.2 Seg A 11.1/3 Seg C 13.6 Seg B	4	Only if required, every Saturday, commencing at 0730 UT and extending up to 1700 UT.
Omega New York Ω/NY	Forestport, New York 43°26'41"N, 75°05'10"W	10.2 Seg D 11.1/3 Seg F 12.5 Seg A,B,C 12.7 Seg G,H 13.6 Seg E	0.25	Only if required, every Saturday, commencing at 1700 UT and extending up to 0230 UT Sunday.
Omega Trinidad Ω/T	Trinidad, West Indies 10°42'06"N, 61°38'20"W	10.2 Seg B 11.1/3 Seg D 12.0 Seg A, E,F,G,H 13.6 Seg C	1	Only if required, every Sunday, commencing at 1130 UT and extending up to 2100 UT.
Omega Hawaii Ω/H	Haiku, Hawaii 21°24'21" N, 157°49'48"W	10.2 Seg C 11.1/3 Seg E 13.6 Seg D	2	Only if required, every Sunday, commencing at 2100 UT and extending up to 0630 UT Monday.

*Frequency is offset according to the current rate for UTC.

NOTES:
(1) Each Wednesday and Thursday 1200 to 2000 UT, transmitter operating at half power for limited maintenance.
(2) Each Tuesday 1200 to 2000 UT, radiated power will be reduced from 150 kw to 90 kw for limited maintenance.
(3) Transmissions will be CW first half hour of each even hour followed by FSK for 1 1/2 hours. CW may be replaced by FSK transmissions as required.
(4) It is planned to transmit every odd hour time signal on FSK for experimental purposes. This will be announced later.
(5) The coordinates of the receiving antenna of the U. S. Naval Observatory control and monitoring station in Washington, D. C. are: 38°55'N, 77°04'W.

NOTES (Continued)

(6) Omega Segment Assignments. The Omega navigational transmitters operate on the UTC system and the transmissions have 8 scheduled segments each, repeating with a period of 10 seconds. Segment A starts at the zero second and repeats each 10 seconds thereafter. Segment E starts at five seconds and repeats each 10 seconds thereafter. These times are synchronized with the U. S. Naval Observatory Master Clock. A schematic of the segment duration is attached.

The Omega Project Management Office controls the phase of the Omega New York station using corrections supplied by the U. S. Naval Observatory. The system maintains internal synchronization relative to Omega New York using very long integration times. All Omega emissions will, therefore, be within 10 μs of the U. S. Naval Observatory Master Clock.

(7) All stations transmit from cesium beam oscillators.

(8) The use of Navy VLF controlled transmissions for precise timing applications is explained in some detail in the U. S. Naval Observatory's Time Service Letter of 30 September 1968. This publication, as well as others, is available free of charge upon request.

(9) For information concerning precise time and frequency services, address your requests to:

Superintendent
Attn: Time Service Division
U. S. Naval Observatory
Washington, D. C. 20390

J. MAURY WERTH
Superintendent

U. S. NAVAL OBSERVATORY
WASHINGTON, D.C. 20390

13 November 1968

NO. 93

DAILY RELATIVE PHASE VALUES, SERIES 4

Reference: (a) Time Service Letter of 30 September 1968

The table gives: (USNO - Station)
Unit = one microsecond

Frequency (kc/s-UTC)		LORAN-C Cape Fear 100	LORAN-C* Johnston I. 100	LORAN-C* Iwo Jima 100	LORAN-C Ejde 100	11 Ω/NY 10.2 1,000+	1 Ω/T 12.0 11,000+	10 Ω/NY 12.5 1,000+	8 Ω/H/D 13.6 25,000+
1968 Nov.	7	- 3.6	---	17.5	- 4.6	765	578	788	913
	8	- 3.6	---	17.5	- 4.9	764	577	787	907
	9	- 3.6	---	17.7	- 4.8	762	578	786	908
	10	- 3.5	---	17.9	- 4.6	763	578	787	912
	11	- 3.4	---	18.0	- 4.5	766	578	787	913
	12	- 3.3	---	18.3	- 4.6	768	578	790	915
	13	- 3.1	---	18.5	- 4.7	769	579	790	921

Frequency (kc/s-UTC)		9 GBR 16.0 18,000+	4 NAA 17.8 3,000+	6 NLK 18.6 12,000+	2 WWVL 20.0 8,000+	3 NSS 21.4	5 NPM 23.4 26,000+	7 NBA 24.0 11,000+	WWVB 60.0 kHz 7,000+
1968 Nov.	7	933	433	459	113	173.4	66	282	983
	8	935	433	460	114	173.1	63	284	985
	9	940	435	457	112	172.9	63	285	984
	10	938	435	464	114	173.1	66	285	984
	11	936	436	462	114	172.7	67	287	985
	12	953	441	462	116	172.5	66	288	---
	13	954	441	464	117	---	74	289	987

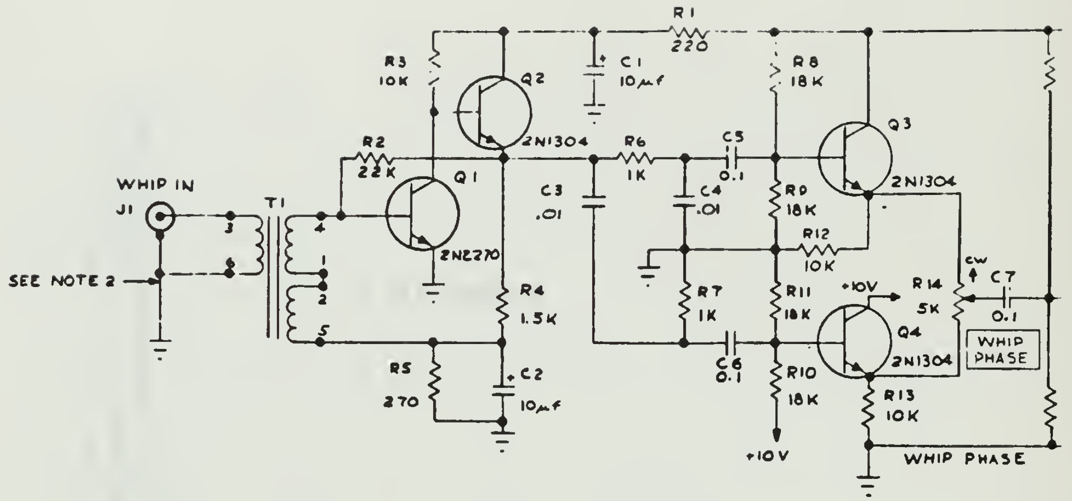
*Measured by USNO Time Reference Station within ground wave range but corrected to refer to USNO Master Clock.

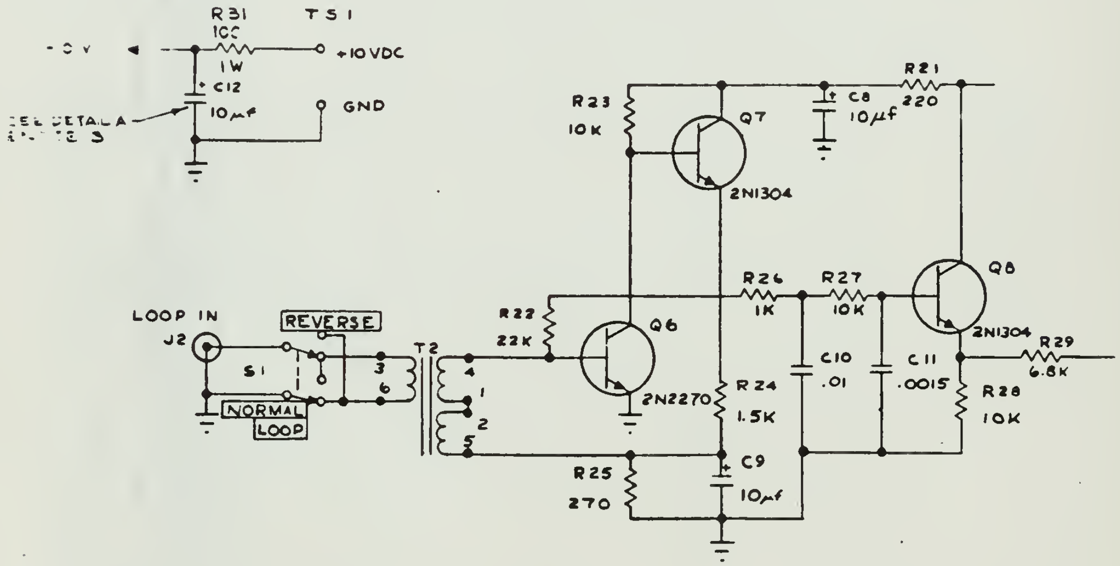
NOTES: (1) Numerous propagation disturbances observed 7 - 13 November.

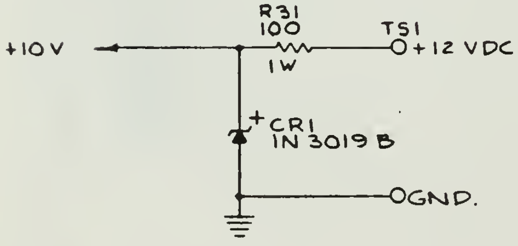
(2) On 28 October 1968 at 2340 UT the National Bureau of Standards Clock #8 in Boulder, Colorado, was measured to be 0.7 microseconds behind the USNO Master Clock in Washington, D. C. Last measurement was made on 22 August 1968 at 1430 UT at which time NBS Clock #8 was 3.7 microseconds ahead of USNO Master Clock. See Daily Relative Phase Values, Series 4, NO. 83.

Appendix D

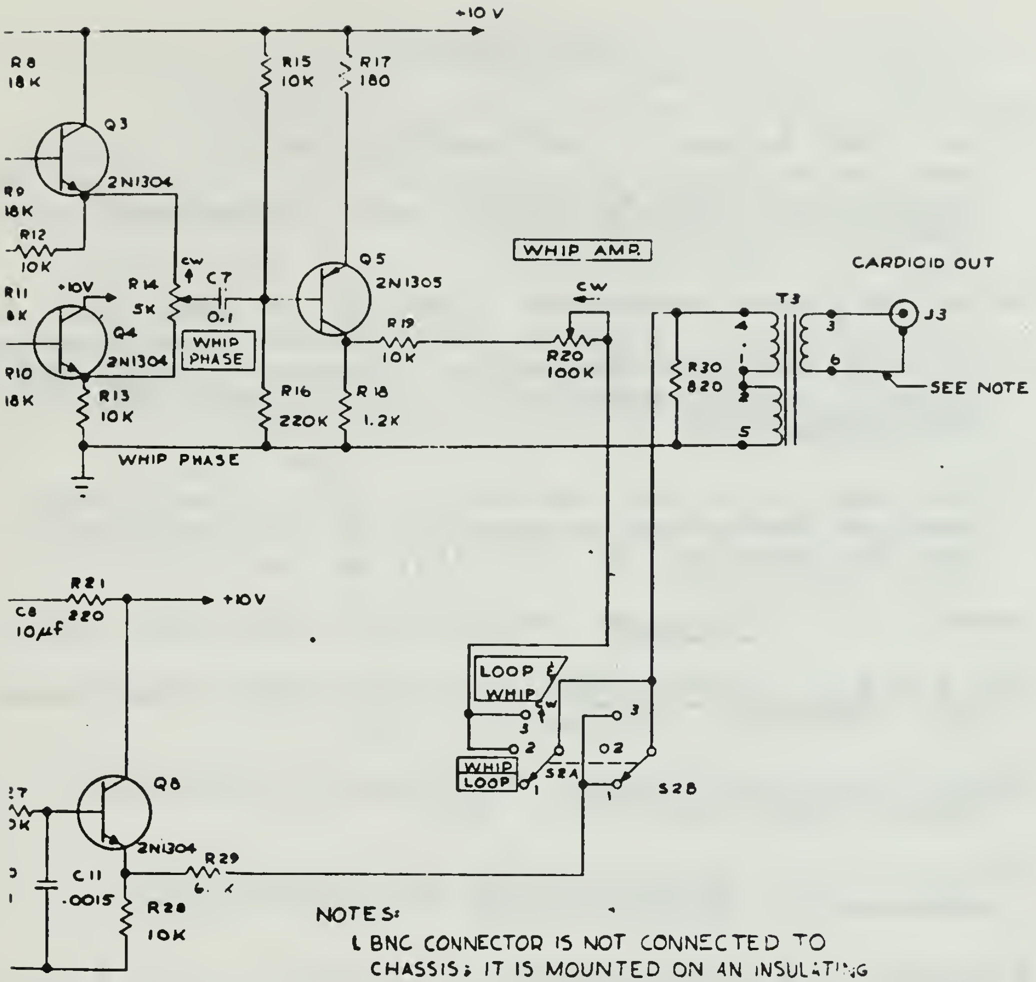
APPENDIX D







DETAIL A



NOTES:

1. BNC CONNECTOR IS NOT CONNECTED TO CHASSIS; IT IS MOUNTED ON AN INSULATING BOARD.
2. INPUT BNC CONNECTORS SHOULD BE CONNECTED WITH A GROUNDING BUS TO GROUND ON TS 1.
3. C 12 IS REPLACED BY CR 1 WHEN UNIT IS OPERATED FROM A 12-VOLT BATTERY INSTEAD OF FROM 599 SERIES RCVR +10 VOLT SUPPLY.
   C 12 IS CONSIDERED STANDARD; CR 1 IS KNOWN AS MOD. 71-9.

TRACOR, INC.		AUSTIN, TEXAS	
DIAGRAM, SCHEMATIC CARDIOID UNIT, MODEL 611			
SIZE 3	CODE IDENT NO	725019	A
SCALE		SHEET	OF

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13. ABSTRACT

A VLF relative navigational system makes use of the fact that, at any given point on the earth, phase delay of a received VLF signal is highly stable and predictable. As the receiver is physically moved, phase delay changes linearly with distance from the transmitting station, so that by keeping track of the phase delay of the received signal from several VLF stations, an accurate plot of geographical position is maintained.

This paper outlines the development of a relatively simple antenna system, composed of two crossed loops and a whip sense antenna to produce a cardiod shaped radiation pattern, which effectively discriminates against the long-way-around-the-world contamination on the short path signal. A means is also devised for electronically rotating the fixed antenna by means of a goniometer which may be stabilized in azimuth by an input from a ship's gyrocompass.

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VLF Propagation						